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Final Elements of RT *Aurigæ*.

Time from light-max. to periastron	$T = 3^{d}.423 \pm 0^{d}.020$
Distance of periastron from node	$\omega = 95^{\circ}.016 \pm 2^{\circ}\ 502$
Eccentricity	$e = 0.368 \pm 0.014$
Velocity of system	$V = +21^{km}.434 \pm 0.399$
Maximum radial velocity	$= +38^{km}.819$
Minimum radial velocity	$= +\ 2^{km}.895$
Single amplitude of curve	$K = 17^{km}.962 \pm 0^{km}.246$
Projection of semi-axis major	$a \sin i = 856{,}500^{km}$

By the least-squares solution the sum of the squares of the residuals was reduced from 28.69 to 22.05. The outstanding residuals are so grouped as to suggest that the orbit is not truly elliptic.

THEORIES CONCERNING THE CAUSE OF LIGHT CHANGE IN *CEPHEID* AND *GEMINID* VARIABLES.

Twelve stars whose light variation is continuous and of short period have now been investigated spectrographically with a considerable degree of completeness. We shall consider the various explanations that have been suggested as to the cause of their variability and test these explanations, as far as possible, by means of the observed facts.

The principal characteristics of stars of this type are:—

1. Their light varies without pause.
2. The amount of their light variation is usually about one magnitude.
3. Their periods are short—a few days only.
4. They are of a spectral type approximately solar; no Orion, Sirian, or Antarian stars having been found among them.
5. They seem to be found in greater numbers in certain parts of the sky, notably in the Milky Way,[13] but exhibit no tendency to form close clusters.
6. All those stars whose radial velocities have been studied have been found to be binaries, whose period of orbital revolution coincides with that of their light change.
7. The orbits, so far as determined, are all small, $a \sin i$ being $2{,}000{,}000^{km}$ or less.

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[13] Miss Clerke, *System of the Stars,* 144, 1890.

8. Their maximum light synchronizes very closely with their maximum velocity of approach, and minimum light with maximum velocity of recession.[14]
9. No case has been found in which the spectrum of more than one component has been bright enough to be recorded in the spectrograms.

The first-mentioned characteristic sharply separates these stars from stars of the Algol type, whose light-curves always contain horizontal straight lines; and the eighth shows that their variation cannot be due to occultation by the dark companion, since in that case minimum must occur at inferior conjunction. The third property makes it imperative that a theory, to be successful, should connect the light variation with the orbital revolution.

In his discussion of the orbit of *ζ Geminorum,*[15] Dr. CAMPBELL suggested tidal disturbances[16] in an atmosphere surrounding the brighter component, due to the gravitational attraction of the darker; and explained the fact that minimum light occurs soon after periastron passage by supposing a reduction of brightness due to a sudden expansion of the gases of the atmosphere under the influence of maximum tidal action when near periastron. That maximum light, instead of minimum, occurs soon after the nearest approach of the two components in the cases of *η Aquilæ* and *δ Cephei,* he thought might be explained by the greater difference of tidal action in different parts of the orbits of these stars, owing to their greater eccentricity.

At that time, however, the orbits of only three stars of this class had been determined, and in the light of subsequent research on other variables of this type, there are serious objections to the general application of this theory.

First, no general relation seems to hold between the time of periastron passage and the time of greatest brilliancy.

Second, the theory in no way explains ALBRECHT'S discovery of the time relation between maximum light and maximum velocity of approach.

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[14] ALBRECHT, *Lick Observatory Bulletin,* **4,** 138, 1907.

[15] *Astrophysical Journal,* **13,** 90, 1901.

[16] The tidal theory appears to have been first suggested by ROBERTS, of South Africa, *Astrophysical Journal,* **2,** 283, 1895.

Third, no increase in the range of brightness variation is found in the case of stars having orbits of greater eccentricity.

Moreover, if the tidal disturbance takes place in the bright star's atmosphere, we should expect to find bright lines in the spectrum, and this has never been observed. If, on the contrary, the disturbance occurs in the denser part of the body, it seems unlikely that the star should lose perceptibly in brilliancy during the few days that elapse before it is again subjected to maximum tidal action.

However, despite these obstacles to making tidal action a chief basis for explaining the light variations of these objects, it is very probable that this action does have a profound influence on the behavior of the system.

A second hypothesis for explaining the variation of stars of this type is that of a resisting medium in which the binary system is supposed to be enveloped, and the impact of whose particles causes the star's advancing side to become heated. This idea was first published by Dr. R. H. CURTISS[17] and has been somewhat elaborated upon by Professor F. H. LOUD.[18] The impact of the particles of a resisting medium of nebulous or meteoric matter might cause variation in a star's light in two ways—first, as the star revolved in its orbit, if it moved at different times with different speed or through portions of the medium having different densities, there would result a difference in the actual rate of emission of light; second, if the star moved like the Moon, keeping always the same face towards its dark companion, the preceding face would, by the impact of particles, be kept constantly hotter than the following side, and, as the star rotated, first the darker and then the brighter side would be presented to the observer.

The hypothesis of a resisting medium has many things in its favor, but chiefly the fact that it accounts for the synchronism of maximum light and minimum positive velocity.

That the variation of the star's light can be accounted for by a change in the rate of light emission is rendered improbable by the following facts:—

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[17] *Lick Observatory Bulletin*, **3**, 40, 1904; and *Astrophysical Journal*, **20**, 186, 1904.

[18] *Astrophysical Journal*, **26**, 369, 1907.

1. In order that the actual emission of light may vary, the star must cool perceptibly during the few days which elapse between successive passages through those parts of the orbit where the bombardment is most fierce. This would necessitate that the disturbance take place only in the outer and rarer parts of the star's atmosphere—a fact which is contradicted by the character of the spectrum.
2. No greater range of light variation is observed in stars having highly eccentric orbits than in those whose orbits are only slightly eccentric, and in general, there is no marked outburst of light when the star is near periastron.

If we make use of the hypothesis of a resisting medium, we must therefore restrict it to the case where the period of rotation of the bright star is equal, or nearly equal, to that of its revolution. Professor LOUD's ideas may, I think, be briefly summed up as follows: Since the star's binary character is betrayed, not by a doubling of the lines but by their periodic shift, one component only is luminous; its light is due to the bombardment of its surface by particles of the medium through which it moves, and to which its companion, since it is non-luminous, must be relatively at rest. The distance between the two components is so small that tidal action tends strongly to equalize the periods of rotation and revolution of the bright satellite; but, owing to the resistance imposed upon its motion, the satellite moves upon an ever-diminishing spiral, its period of revolution shortens, and therefore that period is always a little shorter than the period of rotation. The effect of this lag of the rotation is to cause the heated area on the satellite, produced by meteoric bombardment, to become unsymmetrical, the point of greatest heat moving slowly along the equator into colder regions, leaving behind it a slowly cooling band. To an observer, then, whose line of sight is not perpendicular to the plane of the orbit, the star's light would vary continuously, but the time-interval from minimum to maximum would be shorter than that from maximum to minimum—a well-known distinguishing feature of the light-curves of many variables of this type. Those cases where the asymmetry in the light-curve is reversed or where, as in ζ *Geminorum,* it does not exist, he explains by assuming that the rate of rotation is more rapid than, or equal to, that of revolution. Irregularities in the light-curves are explained by the separate or joint action of three causes: Ellipticity of the orbit, producing greater speed near periastron; "libration," or the optical effect of variation of angular speed in revolution owing to the orbit's eccentricity, while the rotation rate is constant; and variations in the density of the medium.

In the majority of the variables of this class whose orbits are known, the light maximum occurs a little before maximum velocity of approach—instead of a little after or exactly simultaneous with it, as we should expect on this hypothesis. This Loud explains by supposing that the meteoric bombardment induces in some cases not only an increase of light but an increase of absorption, so that we do not at once get the full effect of the maximum light—a supposition whose truth we cannot disprove, though it seems to have little to sustain it.

Whatever the manner in which the impact of meteoric particles may produce the variation of light, it is certain that the work done by the star in imparting momentum to the meteors must tend to shorten the period of revolution; and perhaps a crucial test of the hypothesis may be found in the calculation of the relations between this shortening and the quantity of energy emitted in the forms of light and radiant heat.

In my original article I accordingly calculated these relations and found that, for a star moving in a circular orbit with a period of six days and a speed of 20^{km} per second, through a flock of meteors sufficiently dense to produce by their bombardment a variation in the star's light of 0.8 magnitude, the shortening of the star's period would be seventeen seconds per year. Only one star of this type has been observed to possess a secularly diminishing period. This star is δ *Cephei,* whose period, according to Chandler, shortens by only $0^{\mathrm{s}}.108$ per year, the period itself being between five and six days, and the variation in brightness 0.9 magnitude.

It is true that, between stars situated so close together as are the *Cepheid* variables, tidal action might be very strong and that by its tendency to lengthen the period it might counteract the tendency of the resisting medium to shorten it. It would seem strange, however, that in so many cases the two effects should so exactly balance that no change in either direction could be detected. Besides, there are many binaries —chiefly variables of the Algol type—whose periods are as short and whose components are as closely situated as are those of the *Cepheids,* but in whose periods no secular change has been detected. In fact, the only Algol variable in whose period CHANDLER notes any secular change is, as we have seen, *U Coronæ,* whose period is shortening but which gives no evidence of light variations of the δ *Cephei* or continuous type. It seems possible, indeed, that among the *Cepheid* stars tidal action has arrived at the stage where both bodies are drawn into prolate ellipsoids and each keeps always the same face towards the other, so that the period has no longer any tendency to increase.

Aside from the change of a star's period, there are other considerations which militate against the hypothesis of bombardment as an explanation of continuous light variation. For example, since these stars move at fairly high speed in small orbits, the invisible companion must be a body of considerable mass as compared with the star that we see. Why, then, if the impact of meteoric bodies is sufficient to produce a large percentage of the radiation of one component, does it not make the other also visible? The meteoric bodies cannot remain at rest relative to either of the components, so we must suppose those particles which the bright star picks up to be moving in orbits about the dark component. If these orbits have the same eccentricity as that of the bright star and if the bodies are moving in the same direction as the star, they must move with nearly the same speed and we can have no violent collisions; if they cross the star's orbit at a large angle, then the star's brightest point will not be in front, but at the side; and if they move in retrograde orbits nearly coincident with the orbit of the star, the star should, in a comparatively few revolutions, collect all the meteors near its path, so that all bombardment would cease.

The question now arises whether, in the present state of our knowledge, a more satisfactory hypothesis for explaining the phenomena of these stars can be found. We have seen that it is unlikely that the variation in brightness can be due to an actual change in the rate of light emission, since in that case the character of the spectrum should change radically during the interval between maximum and minimum. It is clear also that the variation cannot be produced by rotation combined with the greater heating of the star's advancing side by the impact of meteoric particles. Since, however, the character of the spectrum indicates the presence of an absorbing envelope about the luminous body of the star, the change in brilliancy may be due to a variation of absorption; and it is to an hypothesis based on this assumption that I now wish to direct attention.

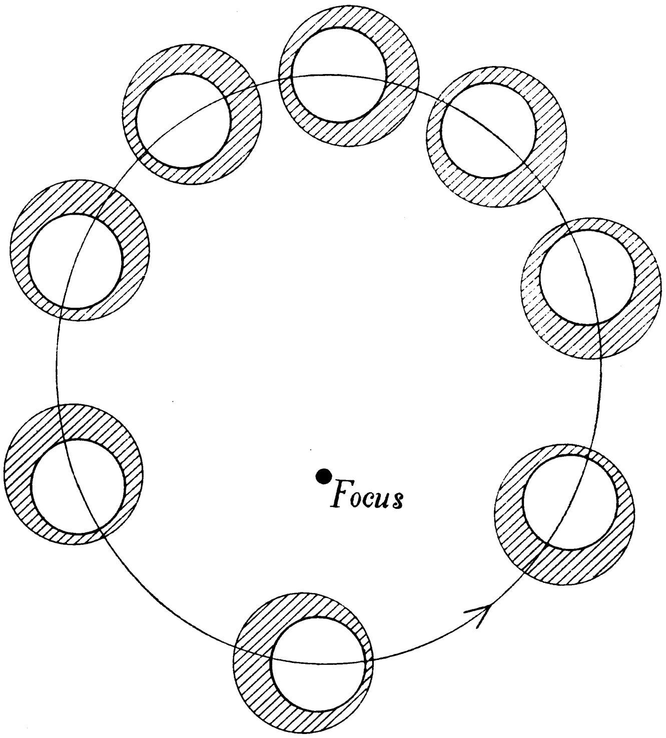
The idea that the variation of light is due to a variation of absorption gains in weight when we recall the similarity between the light- and velocity-curves of these stars, which has been well known since the first orbits were determined and which is especially striking in the case of W *Sagittarii.* The light-curves of stars are ordinarily drawn with ordinates measured in terms of "magnitudes" or other units which express, not the actual amount of light, but the intensity of the observer's sensation, which is proportional to the logarithm of the light. Hence, the similarity of the light-curves and the velocity-curves indicates that the logarithm of the light, and not the light itself, is proportional to the radial velocity. Now, for an absorbing medium of uniform density, the logarithm of the light varies as the thickness, the law of absorption being

$$\log \frac{E}{I} = -\beta x,$$

where x is the thickness of medium traversed, β the coefficient of absorption, and E and I the respective intensities of the emergent and incident light. Therefore, the star's light variation may be explained by assuming an absorbing atmosphere whose depth on the side toward the observer is, within appropriate limits, inversely proportional to the component of the velocity in that direction.

The principal requirements of the case may be met if we suppose a very rare envelope of nebulous matter to surround the darker star of the pair, and that the atmosphere of the brighter component is brushed backward by the friction of this medium so that its depth on the advancing side is less than that on the following. It seems to me to be possible that the Sun's corona is an envelope like this and that coronæ of equal or perhaps greater density may surround all stars of the solar and more advanced types. The orbits of *Cepheid* stars are probably all very much smaller than the orbit of *Mercury* ($a \sin i$ averages about 1,500,000^{km}, while *Mercury's* mean distance is 58,000,000^{km}), and it may be that at a distance from the Sun itself equal to the mean distance between the average *Cepheid* pair the corona would be dense enough to produce the observed effects. If we suppose the absorbing atmosphere of the lucid star to be of low specific gravity, then the envelope of the darker component need not be dense enough to produce by its friction a perceptible shortening of the period.

The shape assumed by the moving star's atmosphere in different parts of the orbit is rudely represented in the figure. The ellipse in the figure has an eccentricity of about one third, which is near the average eccentricity of the *Cepheid* orbits. The atmosphere is represented as spherical but eccentrically placed with regard to a moving spherical star—a condition which is of course only approximately realized. From the figure it is easy to see that maximum light will always occur near the time of minimum positive velocity, and minimum light near maximum positive velocity. The synchronism should be exact if there are no disturbing influences and if the orbit is circular or the resistance varies exactly as the inverse first power of the velocity; for then the depth of the star's atmosphere, measured in any direction, should be inversely proportional to the resolved part of the velocity in that direction. If, however, the resistance varies inversely as the velocity raised to any higher power than the first, and if the orbit be eccentric, then exact synchronism will not hold. In that case, for values of ω between 0° and 180°, the body will be approaching periastron and the distortion of the atmosphere increasing when it is receding from the observer, and *vice versa;* so that maximum



light should occur a little before velocity minimum and minimum light a little after velocity maximum. For values of ω between 180° and 360°, these conditions should be reversed. An inspection of Table III shows a tendency towards fulfillment of this rule, though there are several exceptions. These may be due to several causes, such as inaccuracy of the orbits or of the photometric observations, inequality of density in different parts of the nebulous envelope, and inequalities of brightness on different parts of the star's surface. In several cases the disagreement in the epochs of maximum or minimum light according to different observers would indicate an uncertainty in those epochs sufficient to account for the exceptions to our rule.

The range of light variation will depend on two factors: the specific absorbing power of the bright star's atmosphere,

TABLE III.—VARIABLE STARS OF THE *CEPHEID* AND *GEMINID* TYPES WHICH ARE KNOWN TO BE BINARY.

Star	α 1900.0	δ 1900.0	Max.	Min.	*V* km	*V′* km	*K* km	*e*	ω	*T*	*U*	*a* sin *i*
RT *Aurigæ*	$6^h 22^m.1$	+ 30° 34′	4.9	5.9	+ 21.5	+ 11.7	17.3	0.36	92°.0	$3^d.4$	$3^d.73$	$826,000^{km}$
ζ *Geminorum*	6 58 .2	+ 20 43	3.7	4.3	+ 6.8	— 5.7	13.2	0.22	333	6 .4	10 .15	1,798,000
l *Carinæ*	9 42 .5	— 62 3	3.6	5.0				0.3 ±			35 .53	
X *Sagittarii*	17 41 .3	— 27 48	4.4	5.0	— 15 ±	— 5 ±	15.8 ±	0.45 ±	90 .4 ±	6 .3	7 .01	
Y *Ophiuchi*	17 47 .3	— 6 7	6.2	7.0	— 5.0	+ 10.8	8.5	0.10	209 .2	2 .6	17 .12	1,999,000
W *Sagittarii*	17 58 .6	— 29 35	4.6	5.4	— 28.6	— 18.6	19.5	0.32	70 .0	6 .7	7 .59	1,930,000
Y *Sagittarii*	18 15 .5	— 18 54	5.8	6.6	+ 4.0	+ 17.0	19.0	0.16	32 .0	4 .5	5 .77	1,485,000
κ *Pavonis*	18 46 .6	— 67 21	3.8	5.2							9 .09	
U *Aquilæ*	19 24 .0	— 7 15	6.2	6.9							7 .02	
SU *Cygni*	19 40 .8	+ 29 1	6.5	7.2	— 33.4	— 14.2	25 ±	0.21	345 .8	2 .5	3 .85	1,350,000
η *Aquilæ*	19 47 .4	+ 0 45	3.7	4.5	— 14.2	+ 4.2	20.6	0.49	68 .9	6 .2	7 .18	1,545,000
S *Sagittæ*	19 51 .5	+ 16 22	5.4	6.1	— 12.5	+ 5.8	19 ±	0.35	69 .9	1 .3	8 .38	2,000,000
T *Vulpeculæ*	20 47 .2	+ 27 52	5.5	6.5	— 1.3	+ 15.9	17.6	0.43	111	3 .8	4 .44	969,000
δ *Cephei*	22 25 .4	+ 57 54	3.7	4.6	— 18	— 5	20.5	0.46	272 .3	4 .8	5 .37	1,300,000

TABLE III (*Continued*).—VARIABLE STARS OF THE *CEPHEID* AND *GEMINID* TYPES WHICH ARE KNOWN TO BE BINARY.

Star.	Min.$_v$-Max.$_1$	Max.$_v$-Min.$_1$	Discoverer of Light-Variability.	Discoverer of Binary Character.	Authority for elements of Orbit.
RT *Aurigæ*	$+0^d.16$	$+0^d.36$	ASTBURY	DUNCAN	DUNCAN, *Lick Obsy. Bull.*, **5**, 86, 1909.
ζ *Geminorum*	—0 .2		SCHMIDT	CAMPBELL BÉLOPOLSKY	CAMPBELL, *Astroph. Jour.*, **13**, 90, 1901.
l *Carinæ*	—2½ ±		GOULD	WRIGHT	ALBRECHT, unpublished.
X *Sagittarii*	—0 .2 ±	—1 .3 ±	SCHMIDT	SLIPHER	MOORE, *Lick Obsy. Bull.*, **5**, 111, 1909.
Y *Ophiuchi*	—1 .3	+0 .5 ±	SAWYER	ALBRECHT	ALBRECHT, *Lick Obsy. Bull*, **4**, 132, 1907.
W *Sagittarii*	—0 .1	+0 .2	SCHMIDT	CURTISS	CURTISS, *Lick Obsy. Bull.*, **3**, 36, 1904.
Y *Sagittarii*	+0 .78	+0 .1 ±	SAWYER	CURTISS	DUNCAN, *Lick Obsy. Bull.*, **5**, 85, 1909.
κ *Pavonis*			THOME	WRIGHT	
U *Aquilæ*	—0 .5		SAWYER	ALBRECHT	
SU *Cygni*	+0 .22	+0 .02	MÜLLER and KEMPF	MADDRILL	MADDRILL, unpublished.
η *Aquilæ*	—0 .2		PIGOTT	BÉLOPOLSKY	WRIGHT, *Astroph. Jour.*, **9**, 59, 1899.
S *Sagittæ*	—0 .22	+0 .4	GORE	CURTISS	MADDRILL, unpublished.
T *Vulpeculæ*	+0 .3	+0 .1	SAWYER	FROST	ALBRECHT, *Lick Obsy. Bull.*, **4**, 135, 1907.
δ *Cephei*			GOODRICKE	BÉLOPOLSKY	BÉLOPOLSKY, *Astroph. Jour.*, **1**, 160, 1894.

and the ratio of depth of that atmosphere on the front and rear sides of the star; and the latter in turn will depend also on two factors: the relative densities of the atmosphere and the nebulous envelope through which it is dragged, and the speed of the star. To produce a variation of 0.8 magnitude—*i. e.* in order that the light at maximum shall be double that at minimum, it is of course necessary that the atmosphere on the following side absorb at least half the light emanating from that side of the star, and even with that degree of absorbing power the front side of the star must be laid wholly bare. If, however, the atmosphere on the following side absorb three fourths of the incident light, it need be only twice as deep as that on the preceding side in order to produce the above variation. The atmosphere of the Sun, according to LANGLEY, absorbs from one half to four fifths of the light passing normally through it, the absorption being greatest in the blue end of the spectrum.

Dr. ALBRECHT'S discovery that the maximum intensity of the spectrum of a *Cepheid* variable is shifted toward the violet as the star approaches maximum and redwards again as minimum approaches, is in agreement with the hypothesis of absorption. HALE and ADAMS[19] find a more distinct example of the same phenomenon in their comparison of the spectra of the center and limb of the Sun, in that it was necessary to expose eight to ten times as long at the limb as at the center for the violet, but only four or five times as long at the limb as at the center for the red.

It will be of interest to compare spectrograms of the same star made at maximum and minimum to find out if there be any such changes as HALE and ADAMS found in the solar spectrum in moving from the Sun's center to its limb. None of the plates obtained with the single-prism instrument lends itself to this purpose on account of the low dispersion, and the spectrograms that I obtained of RT *Aurigæ* were taken with too wide a slit.

By an inspection of Professor WRIGHT'S plates of η *Aquilæ*, made with the 3-prism Mills spectrograph, Dr. ALBRECHT[20] found variations in the position of spectral lines as the star's light phase changed from maximum to minimum, which correspond to the changes which he observed in passing from one spectral type of star to another; [21] and the appearance at light minimum corresponds to that of an older-type spectrum, thus indicating an increase of absorption at minimum.

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[19] *Contributions from Mount Wilson Solar Observatory*, No. 17.

[20] *Lick Observatory Bulletin*, **4**, 131, 1907.

If the nebulous envelope which I have supposed to exist about the darker star be similar to the Sun's corona, we may expect the form of the light-curve to vary slightly in a period of several years, since the form of the corona, and hence the relative density of its different parts, vary in a similar period. Such a change has been suspected by CURTISS in the case of W *Sagittarii,* and may to some extent account for the dissimilarity of the light-curves of other stars, derived from sets of observations made several years apart. However, in the present state of photometric work, this question cannot be decided.

In Table III is given a list of such variable stars of the *δ Cephei* and *ζ Geminorum* types as are known to possess a variable radial velocity, together with their orbital elements and such other data as I have thought might be of interest. Column one contains the star's name, columns two and three its position for 1900.0, and the two following columns its magnitude at maximum and minimum brilliancy. V is the velocity of the binary system relative to the Sun, and V' that velocity corrected for the solar motion, or the system's velocity relative to the system of brighter stars about us. K is the single amplitude of the velocity-curve, e the eccentricity, ω the argument of periastron measured in the direction of orbital motion from a fundamental plane at right angles to the sight line, T the time of periastron passage in days after light maximum, U the period of orbital revolution in days, and $a \sin i$ the orthographic projection of the semi-axis major upon the YZ plane. The fourteenth column gives the interval in days from maximum light to minimum velocity of recession, and the fifteenth the interval from minimum light to maximum velocity of recession. The last three columns give the names of the discoverer of light variability, the discoverer of variability of radial velocity, and the authority for the orbital elements given.

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[21] *Lick Observatory Bulletin,* **4,** 90-95, 1906.

It is with pleasure that I acknowledge my indebtedness to Director CAMPBELL, who placed at my disposal the necessary instruments, and who also aided me with advice and encouragement; to Messrs. WRIGHT, MOORE, and ALBRECHT for various suggestions in discussing the hypotheses regarding stellar variability; to Professor CRAWFORD, of Berkeley, who verified the mathematical work; and to Misses HOBE and ALLEN, who performed a part of the computation.

J. C. DUNCAN.

MT. HAMILTON, May 25, 1909.

THE ORBIT OF THE *CEPHEID* VARIABLE STAR X *SAGITTARII*.[1]

The variable brightness of X *Sagittarii* was discovered by SCHMIDT in 1886. Its variability was soon recognized to be similar in type to that of δ *Cephei*, characterized by a regular and continuous change in light, and the inequality of the intervals from maximum to minimum and minimum to maximum.

The variable radial velocity of X *Sagittarii* was detected by Mr. V. M. SLIPHER[2] from his measures of the plates of June 19 and 22, 1904. A series of spectrograms of this star was secured at the Lick Observatory in August, September, and October, 1904, with the one-prism spectrograph equipped with a light 60° prism.[3] The period being so nearly commensurable with a day, these observations were sufficient to determine only seven points of the curve. It was then necessary to wait until the summer of 1905 before observations at intermediate points of the curve could be secured. When the 1904 and 1905 series were measured and reduced by the method described by Mr. R. H. CURTISS[4] it was found that the accordance of the observations, using all of the plates, was not satisfactory, due to differences in exposure, combined with

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[1] A detailed account of this investigation will be found in *Lick Observatory Bulletin*, 157, **5**, 111, 1909.

[2] *Lowell Observatory Bulletin*, **11**, 1904, and *Astrophysical Journal*, **20**, 146, 1904.

[3] For a description of the one-prism instrument, see Mr. R. H. CURTISS's article, *Lick Observatory Bulletin*, **3**, 19, 1904.

[4] *l. c.*